LOX/LH_2 PROPULSION SYSTEM FOR LAUNCH VEHICLE UPPER STAGE -2ND REPORT. TEST RESULTS-

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16. Abstract

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LOX/LH_2 PROPULSION SYSTEM FOR LAUNCH VEHICLE UPPER STAGE
- 2ND REPORT. TEST RESULTS -

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This paper reports the test results of small LOX/LH_2 engines (1,000 kg thrust class) for two propulsion systems, a pump-fed system and a pressure-fed system. The pump-fed system has the advantage of higher performances and higher mass fraction. The pressure-fed system has the advantages of higher reliability and relative simplicity. Adoption of these cryogenic propulsion systems for upper stage of launch vehicle increases the payload capability with low cost. For example, by replacing solid motor of the third stage of H-1A vehicle with the cryogenic stage, the payload capability can be increased from 550 kg to 800 kg. The 1,000 kg thrust class engine was selected for this cryogenic stage by parametric system study. A thrust chamber assembly for the pressure-fed propulsion system was fabricated and tested. The test /377*

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results indicated that it has good performance to meet system requirements. The pump-fed engine system assembled with the igniter and propellant valves was subjected to hot firing tests and showed expected performances.

1. Introduction

Liquid hydrogen/liquid oxygen propulsion systems with small thrust have a high specific impulse and are small in size, increasing the payload capability of a rocket with low cost. For example, it was reported in our first report[1] that by replacing the solid motor of the third stage of a large rocket (H-1A rocket), now in development in our country for launching artificial satellites, with the propulsion system of 1tf{9.8kN}-class thrust, the payload capability increased from 550kg to 800kg-class. Studies for its development are also underway overseas, as the application of the system to an inter-orbit carrier which transports payload from a low circular orbit to a higher orbit can increase the size and weight of the payload against that of a carrier having a solid propulsion system.

With the objective of grasping the technical problems of two propulsion systems, a pump-fed system and a pressure-fed system, to assess their future development possibilities, the authors designed and test-produced the main equipments of the engines which require much development. Their performance tests were carried out at the Rocket Test Center at our Aio Daini Plant.

2. Propulsion Systems

2.1 Turbopump-fed Propulsion System

This is the system which gains thrust by applying pressure with a turbopump to and hot-firing liquid hydrogen and liquid oxygen supplied by propellant tanks. As a result of a trade-off in engine cycles(1), an expander cycle engine(Fig. 1) was chosen. This engine consists of a combustor, turbopump, nozzle extension, propellant start valves, igniter, etc. The fuel, liquid hydrogen, is supplied from a propellant tank at a low pressure, pressurized by a LH_2 pump, and then used for cooling the combustor and part of nozzle extension. Hydrogen, whose temperature has been raised by the cooling of the combustor and nozzle extension, drives the turbine of the turbopump. The higher the driving gas temperature, the larger the turbine output, resulting in a high pressure system.

After driving the turbine, hydrogen gas is sent from the injector to the thrust chamber. Liquid oxygen, which is an oxidant, is sent from the propellant tank at a low pressure and pressurized by LOX pump before being sent from the injecter to the thrust chamber, where it mixes with hydrogen for combustion. Thus, the combustor requires not only the function of generating thrust but that of increasing the temperature of hydrogen in the regenerative cooling unit. For this reason, a channel-shape, copper combustor which has a superior heat characteristic, is used. Before developing the system, however, the heat characteristic needs to be studied well. Also, because there are few other examples of such a small turbopump of small thrust(1tf 9.8kN), its operating characteristics and performances need to be studied. For this purpose, a combustor and a turbopump were test-produced, and separate unit performance tests as well as a system performance test, in combination of the two units, were carried out.

2.2 Pressure-fed Propulsion System

This system gains thrust by directly supplying liquid hydrogen and liquid oxygen to the combustor by pressure-feeding the propellant tanks and hot-firing. Increasing combustion pressure affords a smaller combustor, reducing the weight and increasing the specific impulse. On the other hand, it increases the pressure on the propellant tanks, and their pressure-resistivity requires heavier tank weight. Overall, lower combustion pressure can decrease the system weight. However, because the pressure in the propellant tanks becomes 12kgf/cm^2 {1.18MPa}(1), which is less than the critical pressure of hydrogen, there is a possibility that liquid/gas phase results inside the combustor, causing an unstable combustion. In this study, a combustor was test-produced and its performances at low combustion pressures were studied. Propellant start valves and an igniter were also produced for testing in both systems.

3. Tests

3.1 Turbopump-fed Propulsion System

Main specifications of the engine used in this test are as follows.

Combustion pressure	35.0 kgf/cm^2 {3.45MPa}
Engine mixing ratio	5.5
Turbopump rotation	88,000 rpm
Blowout pressure: LOX pump	68.0 kgf/cm^2 {6.66MPa}
LH_2 pump	55.0 kgf/cm^2 {5.39MPa}

The specifications are slightly different from those employed /378
for the previous report[1], as some pre-existing parts were used this time. However, technical problems can be studied from the operating characteristics and performance data obtained by the engine having the above specifications to assess the directions for future development.

3.1.1 Combustor(Fig.2(a))

It is a channel-shaped regenerative cooling type combustor consisted of a thrust chamber and an injector(Fig.3). Inner cylinder made of copper is mechanically processed and diffusion-bound with a stainless steel outer cylinder(Fig.4). Thrust chamber is cooled by passing liquid hydrogen through this channel. In an expander cycle engine in which hydrogen, having cooled the thrust chamber, is led to the turbopump at an increased temperature and drives the turbine before being injected into the combustor, the length of the thrust chamber is longer than in other engines so that the temperature at the entrance to the turbine meets the system requirement. Same is true for the thrust chamber used in the study of high combustion pressure expander cycle engine[2-4].

The injector consists of 34 coaxial elements and its injecting surface uses a regi-mesh board to accomodate sweat-cooling.

3.1.2 Turbopump(Fig.5)

For the purpose of size and weight reduction, a single-shaft turbopump which drives LH_2 pump and LOX pump by the same turbine was employed(Fig.6). LH_2 pump consists of an inducer and a two-stage /379
impeller, while LOX pump consists of an inducer and a single-stage impeller, and the turbine is a two-stage reaction turbine. There are few other examples of pumps with such small flow and high pressure as this test product. Floating ring seal was used between the LOX pump

and the turbine, and helium gas purge was given to prevent mixing of hydrogen and oxygen. For adjusting thrust in the axial direction, caused by the pressure distribution of the turbopump, balance piston method which had already been developed for the second stage LE-5 engine for the H-1 rocket was employed.

DN-value of the ball bearing was 1.41×10^6, an extremely high value for a bearing for liquid oxygen.

3.1.3 Propellant Start Valve and Igniter

They are used in both engine systems. Propellant start valve (Fig.7(a)) is a poppet valve with an actuater driven by helium gas, and is used for both LH_2 and LOX lines. Igniter(Fig.7(b)) is a torch igniter using a spark plug, which makes it possible to reignite the engine.

3.1.4 Test

The combustor and turbopump were tested separately and then together as a system. Separate unit test was aimed to study the technical problems, operating characteristics and performance data of each equipment as well as to obtain performance data necessary for the system test. The system test was aimed to obtain the operating characteristics and performance data of the expander cycle engine, to assess the feasibility of the rated point studied in the previous report(1) and to gain prospect of the engine development.

3.1.4.1 Combustor /380

Eleven firings each totalling 180 seconds were carried out through the separate unit and system tests. In the unit test, performance data at the design point was obtained and at the same time the range of operation was checked. Testing range is shown in Fig.8(a). Firing was stable within this test range, and the data on firing performances and the combustor's heat characteristics were obtained. Following was found as a result.

1. At the combustion pressure of 25.5 ~ 39kgf/cm^2 {2.50 ~ 3.82MPa} and mixing ratio of 3.2 ~ 8.6(Fig.8(a)), combustion was stable(Fig.9(a)) and the data on combustion characteristics near the rated point was obtained.

2. Average value of characteristic exhaust speed efficiency was 0.991 (Fig.10(a)), which was sufficient for practical use. High efficiency is due to a high temperature (300 ~ 450K) of hydrogen injected into the combustor, which makes easier mixing with oxygen, and the longer thrust chamber length which provided larger heat-receiving area.

3. Heat flux in the regenerative cooling unit coincided well with the design data(Fig.11).

3.1.4.2 Turbopump

The pump was tested a total of 10 times through the separate unit and system performance tests. Operating characteristics up to the maximum rotation of 84,000 rpm were confirmed. Shaft system, seals, etc. worked in a stabled manner also, and the following was found from the obtained data on the operating characteristics and performances.

1. Though extremely small, both LH_2 and LOX pumps satisfied the performance requirements of the system. LH_2 pump, especially, performed above the design point, while LOX pump met the design point(Fig.12).

2. Adjustment of axial thrust by balance piston method was smooth, and operating characteristics well matched the design values and were stable.

3. Floating ring seal between hydrogen gas and liquid oxygen was realized by helium purge. Despite the high rotation, no damage was caused on the seal, providing the basis for application to the actual engine.

4. Performance data on the flow required for cooling the bearing was obtained. In the system test, DN-value of $1.5x10^6$ was achieved although for a short time. There was no abnormality observed on the bearing after the test. Shaft system was stable with no vibration observed.

5. Design and precision manufacturing techniques were established for small size inducer and volute for application to the actual engine.

3.1.4.3 Engine System

Total of four hot-firing tests(total firing time of 74 seconds) brought data on the starting and operating characteristics and performances of the system. Schematic diagram of the system test is shown in Fig. 13. Liquid hydrogen, supplied to the LH_2 pump from LH_2 run tank, is sent to the regenerative cooling unit of the combustor with its pressure raised, to be used for cooling the thrust chamber. Situated at the inlet of the cooling unit is a LH_2 start valve. Hydrogen, once out of the unit, is sent to the turbine, and enters into the injector inside the combustor after driving the turbine.

Liquid oxygen, supplied to the LOX pump from LOX run tank, enters into the injector with its pressure raised. LOX start valve is located at the outlet of LOX pump. The bearing on the LOX pump side is cooled by liquid oxygen, while that on the LH_2 pump side is cooled by liquid hydrogen. Liquid oxygen and hydrogen, after cooling the bearings, are normally circulated back into the inlet of each /381
pump. This time, however, they were disposed instead of recirculating to make the flow adjustment easy, as collecting data on the flow adjustment for cooling the bearings was the purpose of this test. Partially releasing the flow from both pumps and giving leeway in the

circulation inside the pumps cause a work loss. Because of this, the operating point in the test was estimated to be the combustion pressure of 30 kgf/cm^2 {2.94MPa}.

Test results are shown in Table 1. First, starting characteristics were checked by a short firing test. Then, the system operating characteristics and performance data were obtained by a steady-state combustion performance test, which was repeated three times with adjustments made in the engine mixing ratio and coolant flow on the bearings. Combustion pressure met the estimated value.

Combustion test data are shown in Fig.15. Starting was smooth, and a slight overshoot(6%) was observed in rpm and combustion pressure. During steady state there was no vibration caused by combustion, showing stable operating characteristics. There was no abnormality observed in the sample after the test.

Summary of analysis of the test results is given below.

1. Operating characteristics of the system at starting and during steady state operation were satisfactory(Fig.15). Combustor and the turbopump also operated smoothly, with no abnormality observed in the equipment after the test.

2. Based on the test data, cycle limit of the expander cycle engine was calculated[1] and the upper limit of the combustion pressure achieved as a system was determined(Fig.16). The upper limit increases as thrust increases. The pressure at the rated point[1] was less than the upper limit, which validated continuation of development based on this test product.

3.2 Pressure-fed Propulsion System

3.2.1 Combustor

The combustor is a channel-shaped regenerative cooling type combustor(Fig.2(b)), and it is, similar to the combustor for the turbopump-fed system, bound by diffusion. The injector consists of 34 coaxial injection elements.

Main specifications are as follows.

Thrust	700 kgf/cm^2
Combustion pressure	7.0 kgf/cm^2 0.69MPa
Mixing ratio	5.5
Specific impulse	441 s(nozzle area ratio: 100)

3.2.2 Test

The system was tested at the combustion pressure of 6~10 kgf/cm^2 {0.59 ~ 0.98MPa} and mixing ratio of 3~8 for combustion performance, cooling performance and combustion stability. Results showed that regenerative cooling performance of liquid hydrogen was satisfactory, with no problem at low pressure. Despite the low combution pressure, vibration from the pressure was minor, with combustion remaining stable. An example of the test data is shown in Fig.9(b).

Results of observations made on the data are summarized below.

1. Data on characteristic exhaust speed efficiency is shown in Fig.10(b). With different combustion chamber lengths the efficiency is higher for longer length.
2. Copper combustor of channel-shape regenerative cooling type operates smoothly for a wide range of combustion pressure and mixing ratio. Cooling performances are even when the combustion pressure is low.
3. Low combustion pressure does not cause vibration. Combustion remains stable.

4. Conclusion

By test-producing the main equipments, performances explored in the previous report(1) proved to be achievable. Furthermore, various data were obtained for future development. Results of this study are summarized as follows.

1. With both turbopump-fed and pressure-fed propulsion systems, operating characteristics of injector and channel-shape cooling type combustor were satisfactory. Pressure-fed system showed steady performance in both cooling and combustion at low pressure. With turbopump-fed system, high pressure combustion was also possible. These results indicate that there is no major problem area in the development of design and production techniques.

2. Turbopump had no problem in the operating performance of its shaft system, seal and balance piston. Pump performance also satisfied design requirements. There is no major problem area in the development of design and production techniques.

3. Starting and steady state operation characteristics of turbopump-fed engine system were checked by the system test. Design data obtained on the main equipment indicated that they were capable of achieving the performances pursued in the previous report[1].

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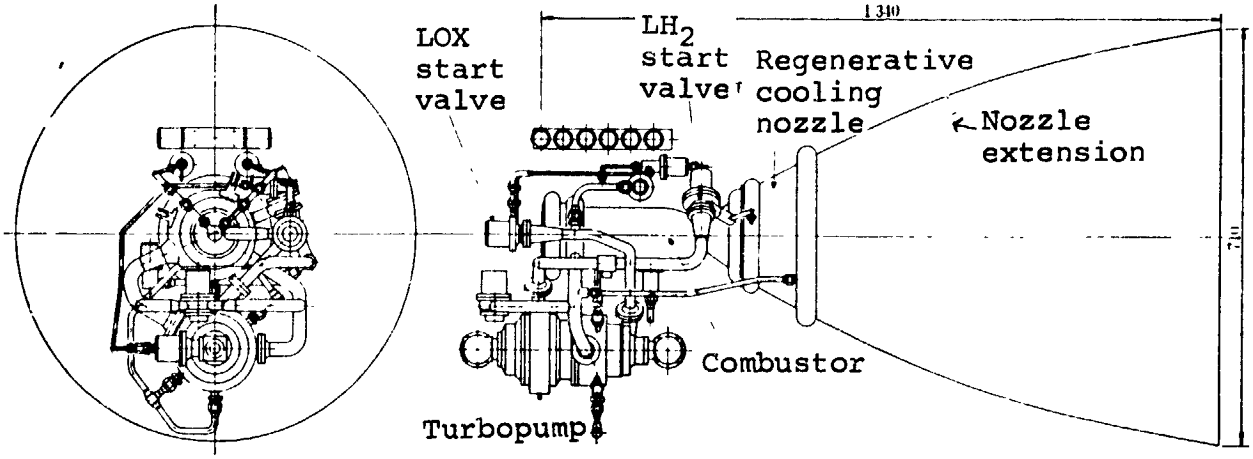
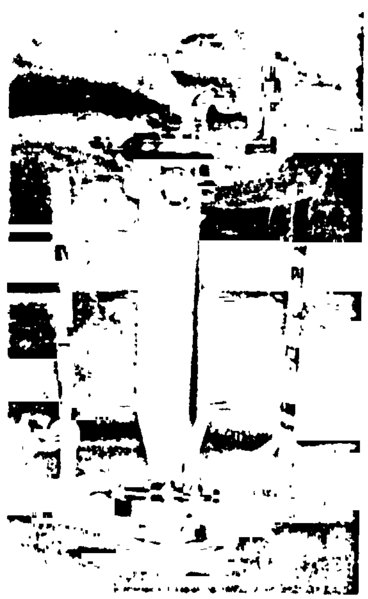


第1図 エクスパンダサイクルエンジン組立図（単位：mm）

Fig. 1 Arrangement of expander cycle engine (unit: mm)

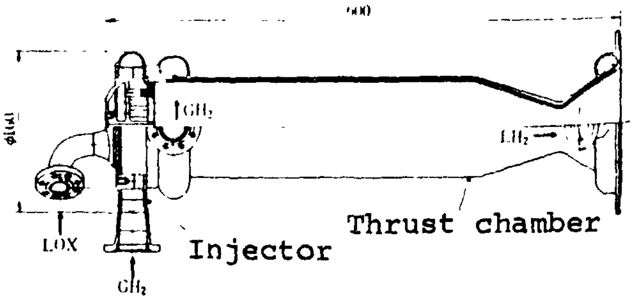


(a) Turbopump-fed propulsion system

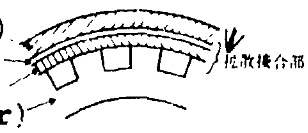
(b) Pressure-fed propulsion system (during hot firing test)

第2図 燃焼器

Fig. 2 Thrust chamber

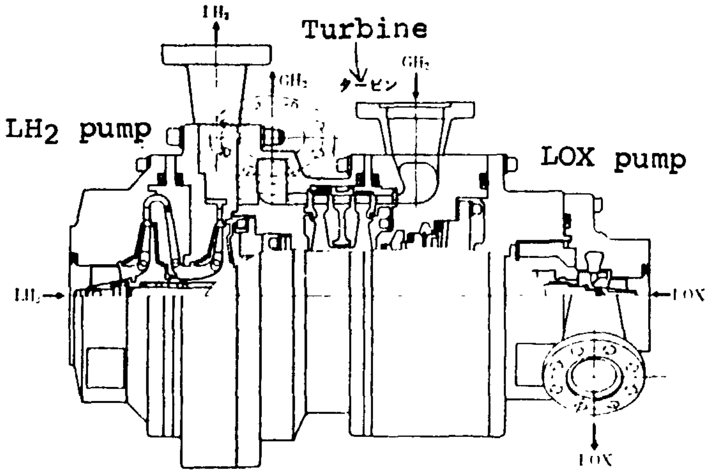


第3図 燃焼器組立図(ターボポンプ式推進系)(単位：mm)
Fig. 3 Arrangement of thrust chamber (pump-fed) (unit: mm)

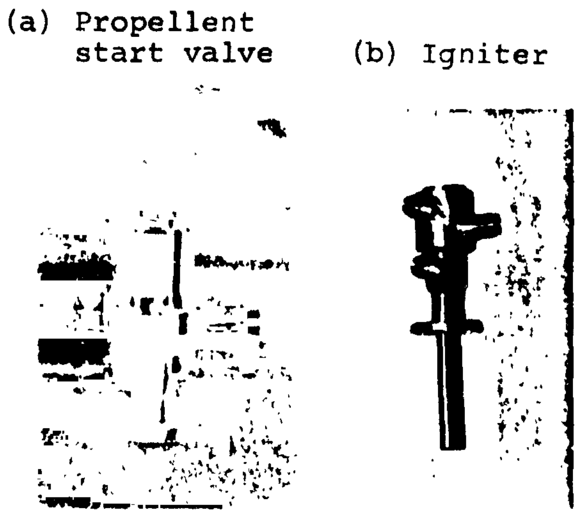


第4図 燃焼室の拡散接合
Fig. 4 Diffusion bounding of thrust chamber

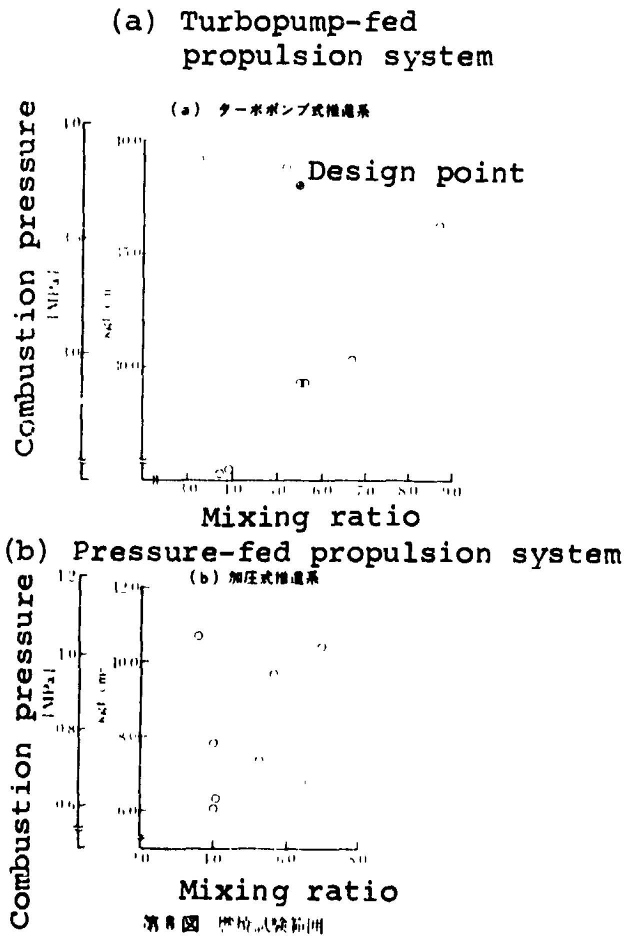
第5図 ターボポンプ
Fig. 5 Turbopump and its components



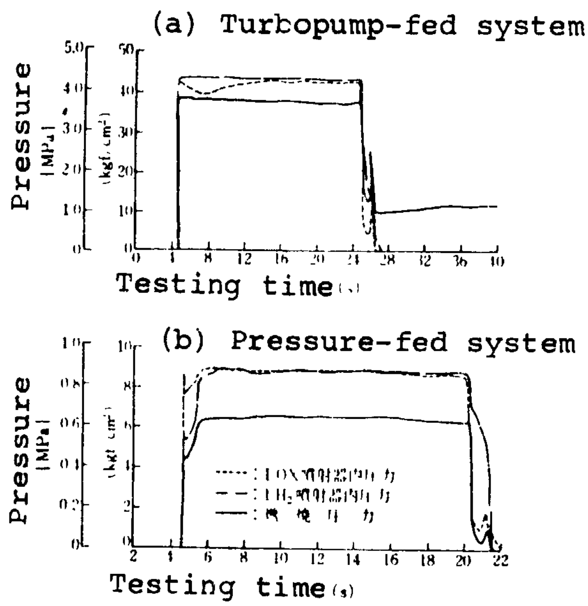
第6図 ターボポンプ組立図
Fig. 6 Arrangement of turbopump



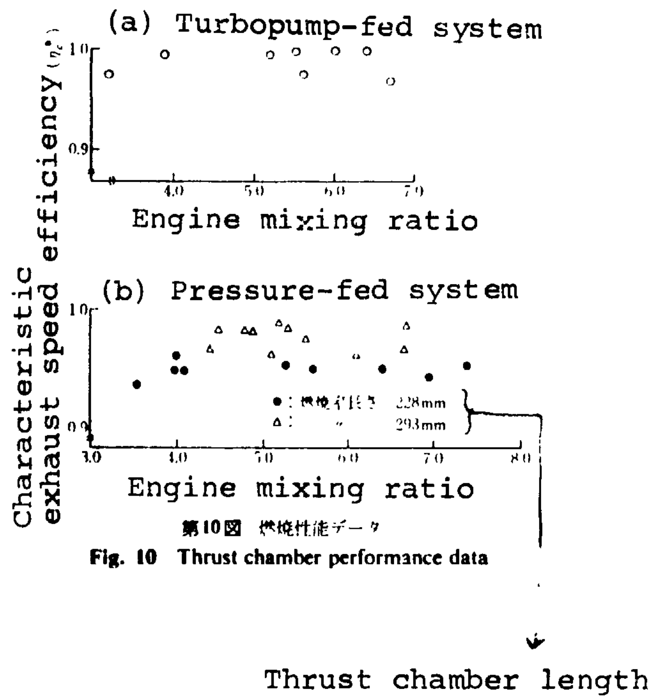
第7図 推進薬スタート弁と点火器
Fig. 7 LOX/LH_2 propellant valve and igniter



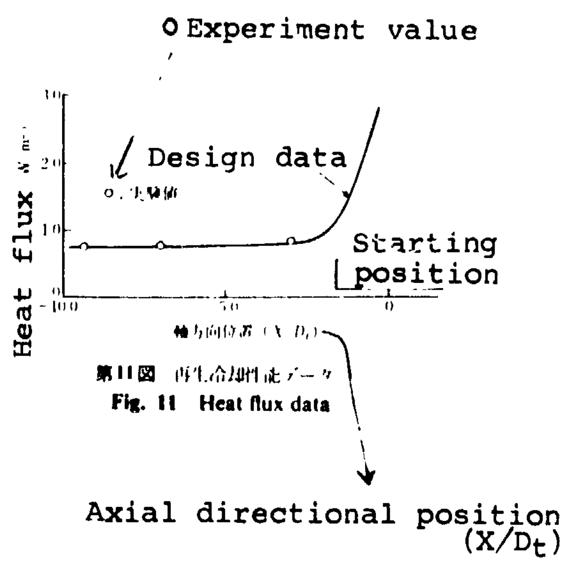
第8図 燃焼試験範囲
Fig. 8 Hot firing test data



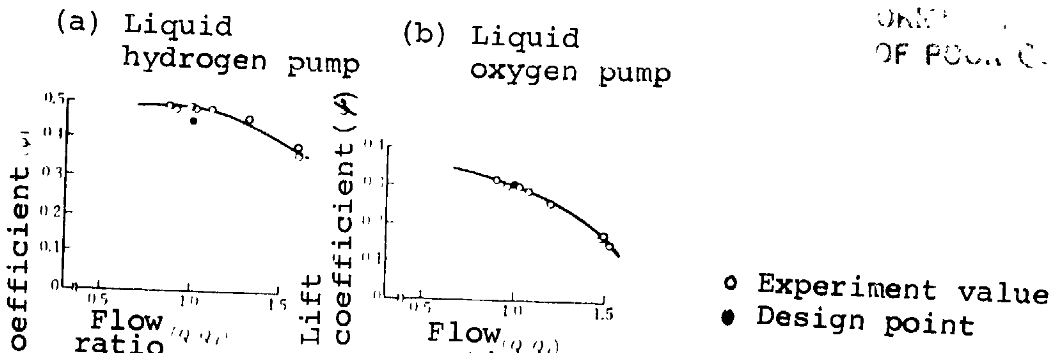
第9図 燃焼試験データ
Fig. 9 Thrust chamber hot firing test data



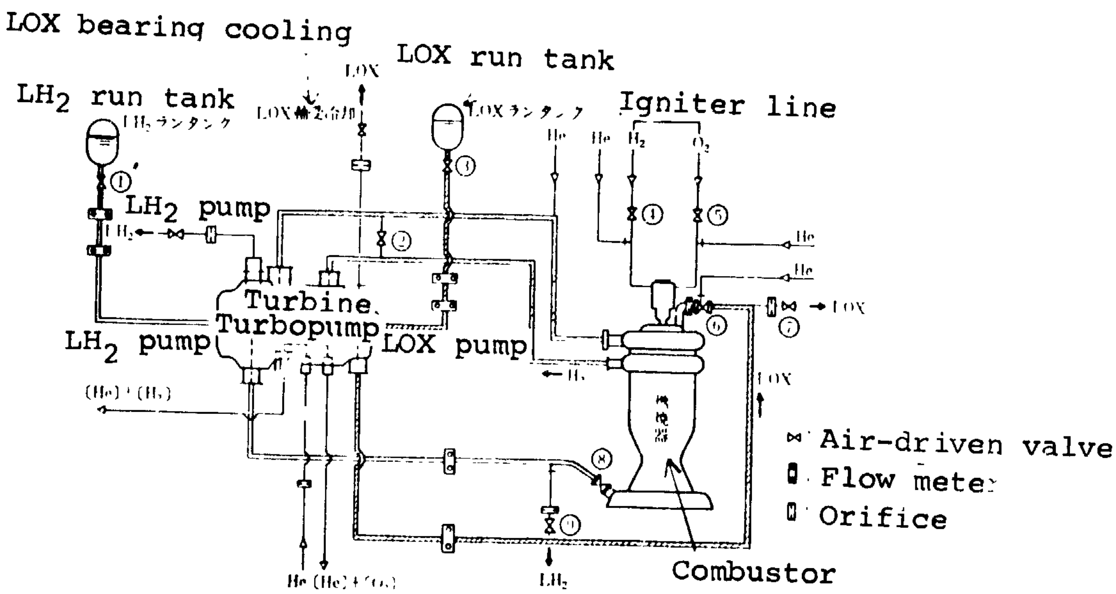
第10図 燃焼性能データ
Fig. 10 Thrust chamber performance data



第11図 再生冷却性能データ
Fig. 11 Heat flux data



第12図 ポンプ性能データ
Fig. 12 Pump performance data

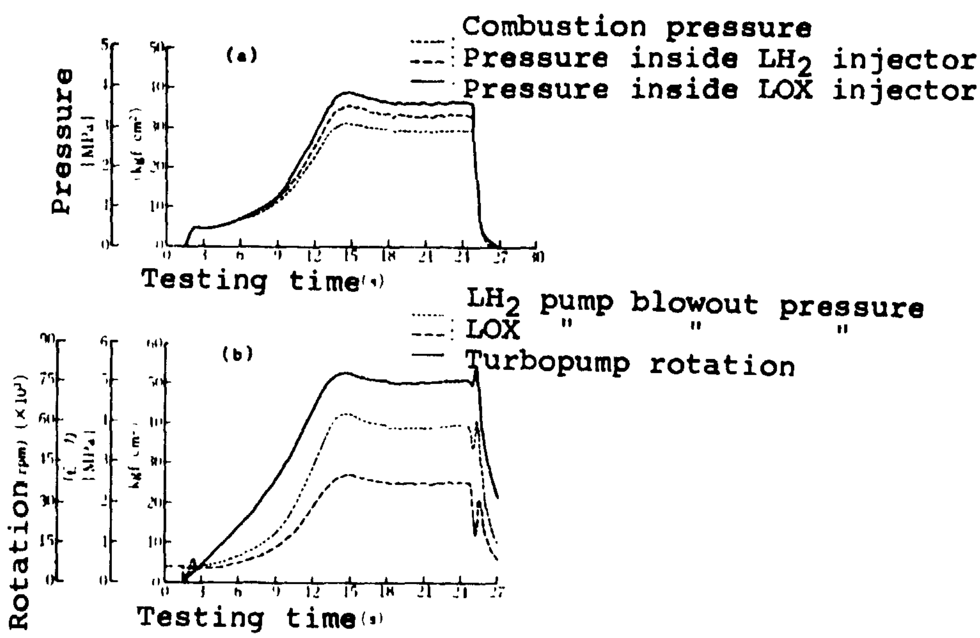


(Note:)
① LH_2 stop valve
② Turbine bipass valve
③ LOX stop valve
④ Igniter hydrogen start valve
⑤ " oxygen " "
⑥ LOX start valve
⑦ LOX pre-cooling valve
⑧ LH_2 start valve
⑨ " pre-cooling valve

Fig. 13 Schematic diagram of pump-fed system test

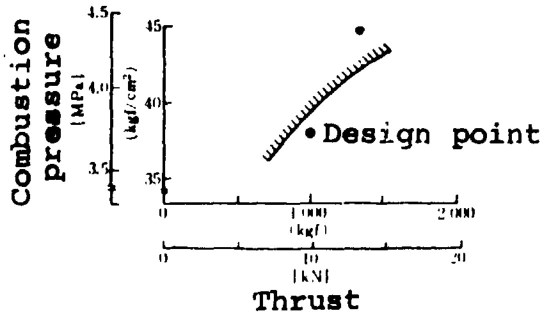
第14図 燃焼試験状況

Fig. 14 Engine hot firing test



第15図 燃焼試験データ

Fig. 15 Engine hot firing test data



第16図 エクスパンダサイクルエンジンのサイクルリミット（混合比 5.5)

Fig. 16 Maximum engine operating pressure

Cycle limit of expander cycle engine(mixing ratio of 5:5)

第 1 表 システム試験結果

Table 1 Test results of pump-fed system

Item / Test No.	Purpose	Testing time (s)	Combustion pressure (kgf/cm²) [MPa]	Mixing ratio	Turbopump rotation (rpm)	Pressure at pump outlet (kgf/cm²) [MPa] LH2	Pressure at pump outlet (kgf/cm²) [MPa] LOX
LT 201	起動確認 (Start check)	10.0	25.5[2.50]	4.7	78 500	60.6[5.94]	40.6[3.98]
LT 202	定常運転 (Normal operation)	20.0	26.1[2.56]	4.9	71 611	58.0[5.68]	40.9[4.01]
ET 301	-	-	28.8[2.82]	5.5	71 005	58.2[5.70]	37.6[3.68]
ET 304	-	24.0	38.6[3.00]	6.7	75 000	60.2[5.90]	38.7[3.79]